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DEPARTMENT OF ENERGY

LSA

LOW-COST SOLAR ARRAY

PROJECT

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Project QUARTERLY REPORT - 10

FOR THE PERIOD JULY 1978 - SEPTEMBER 1978**5101-100**

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
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ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period July through September 1978. It includes reports on silicon material processing, large-area silicon sheet development, encapsulation materials testing and development, Project engineering and operations activities, and manufacturing techniques, plus the steps taken to integrate these efforts.

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SECTION I

INTRODUCTION AND PROJECT OVERVIEW

A. INTRODUCTION

This report describes the activities of the Low-Cost Solar Array Project during the period July through September 1978. The LSA Project is assigned responsibility for advancing solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this and the progress that has been made during the quarter.

The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic modules at a rate greater than 500 megawatts per year and at a price of less than \$500 (in 1975 dollars) per peak kilowatt by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. PROJECT OVERVIEW

In the Project Analysis and Integration Area, the contractor critique of the Lifetime Cost and Performance (LCP) modeling effort was completed and contract action started to begin computer coding of Version I of LCP. With the aid of SAMICS, evaluation of the near-term cost reduction proposals was completed. More than 100 SAMICS runs were completed in this first large practical application of the program, and the program proved to be flexible, to be easy to use, and to be an invaluable aid.

In the Array Technology Cost Analysis effort, the updated SAMICS Cost Account Catalog was received from the Phase II support contractor, and negotiations were completed on the Phase III support contract. SAMICS was used to evaluate a 50¢/Wpk strawman manufacturing sequence prepared by the Production Process and Equipment Area. Development of the SAMIS III computer program continued and several SAMIS documents were published. Numerous requests for information about SAMIS have been received.

The Economics and Industrialization area received Bechtel Corp.'s final report entitled "Terrestrial Central Station Array Life-Cycle Analysis Study," and it approved the industrialization study final report by Gnostic Concepts.

During the quarter, the Project Analysis and Integration Area also performed an active role in the preparation of the solar portions of the Domestic Policy Review.

The Silicon Material Task reported activities in a number of areas during the quarter. Battelle made progress on its design of a 50 MT/yr EPSDU and Si production efforts by Union Carbide and Motorola also advanced.

In other Si production contracts, Dow Corning established hypothetical limits for impurity contents of raw material reactants; SRI International continued efforts on the reaction of $\text{SiF}_4 + 4\text{Na} = 4\text{NaF} + \text{Si}$; Westinghouse completed its detailed design for both the test system components and the test system-laboratory integration; and AeroChem conducted experiments demonstrating the possibility of producing photovoltaic surfaces directly with its process, and, under another contract, spectroscopically examined flames of Na and SiCl_4 . J. C. Schumacher obtained additional experimental data on the thermal decomposition of SiHBr_3 to produce Si.

Working under their joint contract to determine the effects of impurities and process steps, Westinghouse and Dow Corning initiated the third phase of the study with most activity concentrated on the growing of ingots. C. T. Sah, also working on the effects of impurities, extended its computer model for Si solar cell performance.

Materials Research, Inc., using X-ray analysis by the Lang transmission technique, examined Si wafers from Westinghouse to confirm previous results and to study new wafers.

JPL, working on Si processing technologies, constructed a 2-in.-diameter stainless steel fluidized bed reactor and a 3-in.-diameter stainless steel continuous flow pyrolysis reactor.

Mechanisms for the SiCl_4/Na and SiF_4/Na reaction systems were examined by AeroChem Research as part of its contract for development of a model and computer code to describe Si production processes. Lamar University continued analysis of process system properties, with major activities centered on properties of SiCl_4 . Experiments by Los Alamos Scientific Laboratory on the purification of SiH_4 by laser apparatus demonstrated the feasibility of the technique and provided verification of a simplified photochemical model for the process.

The Large-Area Silicon Sheet Task reported developments in shaped ribbon technology, supported film technology, ingot technology, and contact material contracts.

Working under shaped ribbon technology contracts, Mobil Tyco's new EFG furnace became operational and Motorola achieved a growth rate of $55 \text{ cm}^2/\text{min}$ with a single ribbon. Westinghouse completed a manually operated continuous melt replenishment system and installed it in the research web growth facility.

At Honeywell, in the area of supported film technology, two 5 cm substrates passed through the SCIM coater without breaking. RCA Labs completed a series of tests using a laboratory model rotary disc epitaxial reactor.

Working on the advanced Czochralski process, Kayex reported disappointment with its experiments on a low-cost sand crucible. Siltec completed design of a transfer tube, and Texas Instruments converted a Czochralski crystal growing furnace to a continuous growth facility. Varian installed a crystal lift mechanism for its prototype puller, and, in work on multiblade sawing, defined limits for blade thickness tolerances.

Mass spectrometric studies of molten Si in contact with mullite and β' Sialon ($\text{Si}_{6-x}\text{Al}_x\text{N}_8-y$ where $x = 0.75$) were conducted by Battelle Labs. At Coors Porcelain, punched substrates of low-expansion mullite are now routinely being produced for use in the Honeywell program. Eagle Picher's silicon nitride crucibles are now ready for application of the continuously nucleated thermal decomposition coating, and RCA Labs has fabricated die plates of chemical vapor deposition Si_3N_4 and SiO_xN_y .

In the Encapsulation Task, two Request for Proposal packages are being prepared: (1) development of encapsulation systems and (2) life prediction studies of encapsulation systems. The Encapsulation Task also has been selected to monitor near-term cost reduction contracts for an antireflective coating and an encapsulation system substrate.

Negotiations are in progress for an extension of the electrostatic bonding (ESB) contract. Future work will consist of producing suitable ESB modules in semi-production quantities.

The encapsulation failure mechanism associated with the use of glass and polyvinylbutyral has been investigated at JPL by examination of automobile windshields and wing windows on wrecked cars more than 20 years old. Encapsulation material systems have been selected and procurement initiated for the fabrication and test evaluation of candidate low-cost, glass-covered minimodules for 50¢/W strawman designs. Minimodules are to be fabricated and testing initiated within the coming two months and will constitute part of an expanded JPL in-house experimental program to utilize a standard minimodule approach to extensive evaluation of advanced module design and testing methods.

The Battelle Studies 3 and 6 have been completed and the final report has been distributed. A preliminary test plan for the Battelle life prediction study of the Mead, Nebraska, array will be completed and presented to JPL for approval by the end of October 1978.

Endurex, using the recently developed pin-hole free process for ion plating, has conclusively demonstrated that ion-plated coatings will not protect porous metallization systems. Efforts with porous metallization will be abandoned and emphasis will shift to the ion-plated protection of solid metallization.

Dow Corning is preparing encapsulated two-cell modules for its experimental program, and will initiate efforts to assess thin films of silicone as possible UV screens.

A report, "A Preliminary View of Polymer Processing in Encapsulation," has been prepared in-house and will be distributed as an LSA report.

During the quarter, the Production Process and Equipment Area group presented the \$500/kWpk strawman factory and a metallization workshop. Contractors continued work in the areas of technology assessment, surface preparation, junction formation, metallization and contacts, assembly and tests, and advanced module development.

In the area of technology assessment, Sensor Technology reported reduction in costs of cell manufacturing, the University of Pennsylvania completed a comparison of the present crystal-growing costs with projected future costs, and Westinghouse reported the manufacturing of dendritic web cells with efficiencies as high as 15.9%.

Kinetic Coatings reported the effective application of aluminum trioxide to texturized wafers, and RCA continued its work on synthesizing antireflective coatings.

Working in the area of junction formation, SPIRE produced design specifications for a 100 milliamp ion implanter. Lockheed reported the effective use of laser annealing to produce cells with air mass 1 efficiencies on an average of 12.3%, and electron beam annealing equipment was outlined for design for SPIRE.

In other work during the quarter, Motorola reported completion of work on a palladium-nickel metallization formulation, laser scribing equipment was delivered to Sensor Technology and was demonstrated to be effective, and the final three of six contracted modules manufactured from Mobil-Tyco Si ribbon material were delivered.

The Engineering Area continued work on array design guidelines, reliability-durability requirements, and array specifications and standards.

In the area of design guidelines, Bechtel and Boeing submitted draft final reports. The Bechtel contract generated data defining optimum module/array structural configurations for central power applications. Review of the Boeing air-supported module enclosure study results indicates that the concept has potential cost advantages. In-house activities included improving the series/parallel computer program, initiating a contract to develop residential module design guidelines and requirements, and issuing an RFP for a design requirements for electrical termination study applicable to 1986 modules.

In the area of reliability-durability testing, in-house efforts began on characterizing the mechanical breaking strength of Si solar cells. In work on module soiling, a particulate deposition chamber was designed and a data collection agreement was reached with the South Coast Air Quality Management District. Construction began on a combined high voltage stress and dust accumulation field test installation.

A report on recent thermal testing activities included the new test method for measuring nominal operating cell temperature. Preliminary drafts of design and test specifications for future intermediate load center and residential modules were submitted to review. Support was provided to SERI for development of the Interim Performance Criteria draft outline.

The Operations Area reported that a total of 36.2 kW of Block III modules for the Large-Scale Production Task were delivered during the

quarter, an improvement over the previous quarter but still a significant gap between production projection and actuals. The first of three new temperature-humidity chambers became operational, with the result that no modules had to be sent off Lab for testing. Environmental testing of Block III qualification and production samples continued, and three types of developmental modules and six types of commercial modules were also tested.

The bringing on line of the Point Vicente Site completed the network of remote sites for field testing. At the JPL Site, routine testing procedures were tightened up. Five dirt accumulation tests were performed during the quarter, two using the field data system and three using the large area pulsed solar simulator.

Due to differences in spectral response between production modules and reference modules, a new group of reference cells was fabricated for Motorola. In addition, deviations of greater than 3% between measurements at JPL and two vendors have occurred, necessitating an investigation into the causes of the discrepancies. Preparations are under way to provide reference cells to the Phase I contractors for the flat-plate PRDA experiments.

Failure analysis activity for the quarter included the generation of 21 new P/FRs and the closure of 19 analyses. At the end of the quarter, the reporting system had a total of 347 P/FRs, of which 246 had been closed.

SECTION II

PROJECT ANALYSIS AND INTEGRATION AREA

A. PLANNING AND INTEGRATION

The contractor critique of the Lifetime Cost and Performance (LCP) modeling effort is complete with contract action in progress to begin computer coding of Version I of LCP. The software design document for LCP has also been completed. The LCP development activities were summarized at the 10th Project Integration Meeting.

Extensive planning support has been provided for the management and implementation documents for the Photovoltaic Program Lead Center.

The Project Analysis and Integration participation in the evaluation of the near-term cost reduction proposals has been completed. During this evaluation, SAMICS was used to acquire an independent estimate of the manufacturing cost savings possible from the adoption of each proposed improvement. More than 100 SAMICS runs were completed in this first large practical application of the program. The program proved to be extremely flexible and easy to use and was an invaluable aid in normalizing the proposed cost savings portion of the evaluation procedure.

B. ARRAY TECHNOLOGY COST ANALYSIS

The updated SAMICS Cost Account Catalog was received from the Phase II SAMICS support contractor, Theodore Barry and Associates. The negotiations were completed on the Phase III support contract, which is to concentrate on validation of indirect requirements relationships.

A 50¢/Wpk strawman manufacturing sequence and technology description was prepared by the Production Process and Equipment Area and evaluated in detail with SAMICS by the Project Analysis and Integration Area. The results, presented at the 10th Project Integration Meeting, were quite encouraging and indicated the possibility of price reductions below 50¢/Wpk.

Development of the SAMIS III computer program continued. JPL internal documents published and distributed this quarter include "SAMIS Program User's Guide," 5101-60; "SAMIS III Design Document," 5101-70; and "SAMIS III Computer Program Source Code," 5101-71.

Numerous requests for information about SAMIS have been received and responses have been sent to 15 requesters, including seven universities, one of which is in Spain, and eight companies, four of which are outside the photovoltaics industry (Merck and Company, Celanese Plastics Company, Pritsker and Associates, and Frito-Lay, Inc.).

C. ECONOMICS AND INDUSTRIALIZATION

The final report has been received from the Bechtel Corp. on "Terrestrial Central Station Array Life-Cycle Analysis Support Study."

Data reduction continued this quarter for the experimental study of insolation and temperature effects on module power output. The indoor solar insolation data has been coded and the computer runs are in progress.

Work has continued on the preparation of an Si material position paper. This will present and evaluate the various options to ensure an adequate supply of Si in the 1981-85 time period.

The LSA Project Analysis and Integration Area had a very active and pivotal role in the preparation of the solar portions of the Domestic Policy Review. The LSA support for the SERI Venture Analysis was completed this quarter.

The Industrialization Study final report, prepared by Gnostic Concepts, Inc., has been received and approved and is available to those interested. The study deals with the likely prospects for the future industrialization of mass production techniques for the production of low-cost photovoltaic systems. Three classes of risk are considered -- technical, market, and product -- and the implications with respect to types of firms likely to invest and the conditions necessary for such investment are discussed. Gnostic Concepts is also pursuing a follow-on to the above study designed to discover if any of the advanced materials -- Cds, amorphous Si, etc. -- are ready for a technology development effort leading to industrialization.

SECTION III

TECHNOLOGY DEVELOPMENT AREA

A. SILICON MATERIAL TASK

The objective of the Silicon Material Task is to establish by 1986 an installed plant capability for producing silicon (Si) suitable for solar cells at a rate equivalent to 500 MWpk of solar arrays per year and at a price of less than \$10/kg. The program formulated to meet this objective provides for development of processes for producing either semiconductor-grade Si or a less pure, but utilizable (i.e., a solar-cell-grade) Si material.

1. Technical Goals

Solar cells are presently fabricated from semiconductor-grade Si, which has a market price of about \$65/kg. A drastic reduction in price of material is necessary to meet the economic objectives of the LSA Project. One means for meeting this requirement is to devise a process for producing an Si material that is less pure than semiconductor-grade Si. However, the allowance for the cost of Si material in the overall economics of the solar arrays for LSA is dependent on optimization trade-offs, which concomitantly treat the price of Si material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for the optimization trade-offs concurrently with the development of high-volume, low-cost processes for producing Si.

2. Organization and Coordination

The Silicon Material Task effort is organized into four phases. As Table 3-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade Si will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells will be investigated. This body of information will serve as a guide in developing and assessing processes (in Part III) for the production of solar-cell-grade Si. The process developments in Parts I and III will be accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various Si-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies, and the most promising process will have been selected.

Phase II will be to obtain process scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from

Table 3-1. Organization of the Silicon Material Task Effort

Phase/Part	Objective
Phase I	Demonstrate the technical feasibility and practicality of processes for producing Si.
Part I	Establish the practicality of a process capable of high-volume production of semiconductor-grade Si.
Part II	Investigate the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells.
Part III	Establish the practicality of a process capable of high-volume production of solar-cell-grade Si.
Part IV	Evaluate the relative commercial potential of the Si-production processes developed under Phase I.
Phase II	Obtain process scale-up information.
Phase III	Conduct EPSDU operations to obtain technical and economic evidence of large-scale production potential.
Phase IV	Design, install, and operate a full-scale commercial plant capable of meeting the production objective.

which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of Experimental Process System Development Units (EPSDU).

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, EPSDUs will be used to obtain technical and economic evidence of large-scale production potential. In the EPSDU phase (i.e., Phase III) there will be opportunities to correct design errors; to

determine energy consumption; to establish practical operating procedures and production conditions for process optimization and steady state operation; and to more realistically evaluate the requirements for instrumentation, controls, and on-line analyses.

In the final phase of the Silicon Material Task (i.e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The EPSDU and the commercial plant will be operated concurrently for some time so as to permit the use of the EPSDU for investigations of plant operations; i.e., for problem-solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of the Silicon Material Task will be conducted in supporting efforts. These supporting subtasks will be accomplished under contract and by an in-house JPL program.

3. Silicon Material Task Contracts

Eighteen contracts are in progress and are listed in Table 3-2.

4. Silicon Material Task Technical Background

a. Processes for Producing Semiconductor-Grade Si

1) Production of Si by Zn Reduction of SiCl_4 -- Battelle.

The contract with Battelle Columbus Laboratories is for development of the reaction for the Zn reduction of silicon tetrachloride (SiCl_4) using a fluidized bed reactor as an economical means for producing Si. Based on calculations by Battelle and Lamar University, this process has the potential for a total product cost between \$9.12 and \$9.68/kg Si for a 1000 MT/yr plant.

2) Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. The Union Carbide contract is for the development of processes for the production of silane (SiH_4) and for the subsequent deposition of Si from SiH_4 . The SiH_4 process includes systems for the redistribution of chlorosilanes and the hydrogenation of metallurgical-grade Si and the by-product SiCl_4 to trichlorosilane (SiHCl_3), which can be used as a feed for redistribution. The free-space reactor and the fluidized bed reactor are techniques being investigated as the means for Si deposition.

3) Production of Si by $\text{SiF}_4/\text{SiF}_2$ Transport -- Motorola.

The Motorola contract is for the development of a process for the conversion of metallurgical-grade Si into semiconductor-grade Si using $\text{SiF}_4/(\text{SiF}_2)_x$ transport purification reaction steps.

b. Effects of Impurities and Processing on Solar Cell Performance

1) Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells -- Westinghouse/Dow Corning. The objective of this program is to develop and define purity requirements for solar-cell-grade Si by evaluating

Table 3-2. Silicon Material Task Contractors

Contractor	Technology Area
AeroChem Research Princeton, New Jersey (JPL Contract No. 954560)	Nonequilibrium plasma jet process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954777)	Si halide-alkali metal flames process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954862)	Model of Si hydride and halide reactions
Battelle Columbus, Ohio (JPL Contract No. 954339)	Zn/SiCl ₄ fluid bed reactor process
Dow Corning Hemlock, Michigan (JPL Contract No. 954559)	Electric arc furnace process
Lamar University Beaumont, Texas (JPL Contract No. 954343)	Technology and economic analyses
Lawrence Livermore Laboratory Livermore, California (NASA Defense Purchase Request No. WO 8626)	Impurity concentration measurements in Si
Los Alamos Scientific Laboratory Los Alamos, New Mexico (NASA Defense Purchase Request No. WO 8628)	Laser purification of SiH ₄
Materials Research Salt Lake City, Utah (JPL PO No. JR-672583)	X-ray analysis of Si wafers
Motorola Phoenix, Arizona (JPL Contract No. 954442)	SiF ₄ /SiF ₂ transport process
National Bureau of Standards Washington, D.C. (NASA Defense Purchase Request No. WO 8604)	Impurity concentration measurements

Table 3-2. Silicon Material Task Contractors
(Continuation 1)

Contractor	Technology Area
Sah, C. T. Associates Urbana, Illinois (JPL Contract No. 954685)	Effects of impurities
Schumacher, J. C. Oceanside, California (JPL Contract No. 954914)	Production of Si from bromosilanes
SRI International Menlo Park, California (JPL Contract No. 954471)	Na reduction of SiF ₄ process
Texas Instruments Dallas, Texas (JPL Contract No. 955006)	Rotary drum reactor process
Union Carbide Sisterville, West Virginia (JPL Contract No. 954334)	Silane/Si process
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954331)	Effects of impurities on solar cells
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954589)	Plasma arc heater process

the effects of impurities and processing on the performance of solar cells. A secondary goal is to generate data forming a basis for cost-tradeoff analyses of Si solar cell material.

2) Effect of Impurities -- C. T. Sah Associates. Deep-level transient spectroscopy measurements are to be used for correlations with the development of a model for solar cell performance.

3) X-Ray Analysis of Si Wafers -- Materials Research Inc. This is for a non-destructive study of the crystallographic structure defects in Si wafers deliberately doped with impurities.

4) Impurity Concentration Measurements in Si -- Lawrence Livermore Laboratory. Impurity concentrations in Si are to be measured using neutron activation analysis and spark source mass spectroscopy.

c. Processes for Producing Solar-Cell-Grade Si

1) Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Process -- Dow Corning. The Dow Corning contract is for the development of a process for improving the purity of Si produced in the arc furnace by using purer raw materials and for the further purification of the Si product by unidirectional solidification.

2) Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 Process -- SRI International. This contract is for the development of a two-step process for the production of Si. The steps are (1) the reduction of silicon tetrafluoride (SiF_4) by sodium (Na) to produce high purity Si and (2) the further purification of this product.

3) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse. This contract with Westinghouse is for the development of an electric arc heater process for the production of Si using the reaction for the reduction of $SiCl_4$ by Na.

4) Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of Chlorosilanes -- AeroChem Research. The objective of this program is to determine the feasibility of the production of high purity SiH_4 or solar-cell-grade Si using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes are being studied.

5) Production of Si Using Si Halide-Alkali Metal Flames -- AeroChem Research. The objective of this contract is to determine the feasibility of the use of flame reactions involving Si halides and alkali metals for producing Si.

6) Production of Si from Bromosilanes -- J. C. Schumacher. The objective of this contract is to determine the feasibility of using bromosilanes as the appropriate intermediates to produce Si.

7) Production of Si Using a Rotary Drum Reactor -- Texas Instruments. This contract is for a two-step, closed-cycle process for production of Si. In Step 1, $SiCl_4$ reacts with metallurgical-grade Si, and the resulting gas is quenched to yield $SiHCl_3$. In Step 2, $SiHCl_3$ decomposes in a rotary drum reactor to produce $SiCl_4$ and high-purity Si.

d. Supporting Contracts

1) Evaluation of Si Production Processes -- Lamar University. The objective of this contract is to evaluate the potentials of the processes being developed in the program of the Silicon Material Task. The economic evaluations will be based upon analyses of process-system properties, chemical engineering characteristics, and costing-economics. The evaluations will be performed during all phases of the Task, using information that becomes available from the various process development contracts.

2) Impurity Concentration Measurements -- National Bureau of Standards. Methods for measurements of impurities at ppba levels are to be developed.

3) Model of Si-Producing Reactions -- AeroChem Research. This contract is for the formulation of a model and a computer code for the description of several of the Si processes now under development.

4) Purification of SiH_4 by Laser Apparatus -- Los Alamos Scientific Laboratory. This is a study of the removal of impurities, particularly boron, phosphorus, and arsenic, from SiH_4 using a laser.

5. Summary of Progress

a. Production of Si by Zn Reduction of SiCl_4 -- Battelle. Progress was made in finalizing the design of the EPSDU sized at 50 MT/yr of Si. Major simplifications of the design were effected by reducing the temperature (from 500°C to 350°C) of the zinc/zinc dichloride (Zn/ZnCl_2) byproduct recycle system and by eliminating two of the four strippers (solids condensers) by recognizing that small quantities of ZnCl_2 escaping a condenser can be handled downstream in the process. Experimental work gave limited but encouraging evidence of particle size separation in the fluidized bed. Intended materials of construction were tested for compatibility with process stream components, with encouraging results.

b. Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. During this period, the activities were performed on schedule. The SiH_4 production process development unit completed its Phase I feasibility demonstration of 182 hours total continuous steady-state operation. Epitaxy analysis of SiH_4 produced from this operation gave n-type Si having film resistivities of up to 120 ohm-cm.

The free-space reactor was operated for eight consecutive SiH_4 pyrolysis experiments, at an Si production rate of 0.45 kg/hr, without dismantling or servicing the reactor. Several methods were investigated for converting the free-space reactor powder into a more suitable feedstock for Si melters. Loose powder sintering did not densify the powder sufficiently. The fluid-bed reactor was operated continuously for 48 hours with a mixture of 1% SiH_4 in helium as the fluidizing gas. A high SiH_4 pyrolysis efficiency was obtained without the generation of excessive fines. In addition, an interim technical report on the subject of "High Frequency Capacitive Heating of Silicon Particles" was issued.

c. Production of Si by $\text{SiF}_4/\text{SiF}_2$ Transport -- Motorola. Progress was continued in the preliminary design of a 1 kg/hr Si experimental process with the support of Raphael Katzen Associates, an engineering subcontractor. The process unit operations tentatively include: (1) a vertical packed-bed reactor, (2) a scraper condenser with sectional temperature control, (3) the use of a Moyno pump to separate the low-pressure (0.5 torr) reaction system from the relatively high-pressure (150 torr) Si product harvesting system, and

(4) a chemical vapor deposition harvesting unit utilizing a continuous recirculation of Si substrate seeds. Experimental support work confirmed the potential usefulness of the proposed scraper condenser.

d. Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Process -- Dow Corning. Hypothetical limits were established for the impurity contents of both raw material reactants based on experimental data from a one-week material-balance run using an industrial-size arc furnace and the Si product using melt segregation data. The hypothetical limits are structured to produce a solar-grade Si having a resistivity of 0.3 ohm-cm, corresponding to a boron (B) content of 1.7 ppma, the approximate maximum in the plot of solar cell conversion efficiency versus resistivity. Hence, arc furnace Si product, before unidirectional solidification, is limited to 2 ppma of B, 0.8 ppma of phosphorus (P was deliberately set to prevent over-compensation of B), 100 ppma of aluminum, and a total impurity concentration limited to 400 ppma. Dow Corning concludes that both carbon black and activated charcoal meet the set limitations for raw material reactants.

e. Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 -- SRI International. Further effort continued on the reaction $SiF_4 + 4Na = 4NaF + Si$. Emphasis has included an enlarged reactor and optimizing the sodium feed system, using a number of materials of construction for the feed system. The leaching process was expanded to handle 2-kg batches of reaction products.

Further research in the leaching process has shown that, using eight leach steps in 1.0N sulfuric acid, virtually complete separation of the Si was accomplished; up to 90% yield of Si was accomplished by this procedure. In addition to considerable effort in leaching separation, some effort was recently devoted to separation of the Si by melting the reaction products. This method has thus far been successful in that the Si separated from the NaF. For this Si, only nickel was found as a significant impurity by emission spectroscopy.

f. Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse. Detailed design was completed for both the test system components and the test system-laboratory integration. Procurement, fabrication, and assembly of equipment proceeded. Analysis of the reactor indicated that the Si skull wall thickness can be maintained at suitable equilibrium values. Reevaluation of process economics for the present mode (condensation) of product separation indicates an estimated product cost of \$9.42/kg Si (1975 \$) based on a 3000-MT Si/yr plant employing recycle of by-products.

g. Production of SiH_4 Using a Nonequilibrium Plasma Jet for the Reduction of Chlorosilanes -- AeroChem Research. Experiments demonstrated that the electrical resistivity of amorphous Si films made with the nonequilibrium plasma jet apparatus can be reduced by doping with phosphorus, offering the possibility of producing photovoltaic surfaces directly by the process. The technical effort was terminated as required by the contract schedule, and the final report was written.

h. Production of Si Using Si Halide-Alkali Metal Flames -- AeroChem Research. Spectroscopic examination of flames of Na with SiCl_4 indicate the presence of Si atoms as intermediates in the reaction. Experiments in a scaled-up flow tube have shown that a flame of Na and SiF_4 in a low-temperature reactor produces mostly Na_2SiF_6 , but a higher temperature of 1000°K is sufficient to prevent the formation of Na_2SiF_6 , yielding NaF and Si in a stoichiometric ratio.

In experiments simulating the Westinghouse arc heater process, for the Ar, H_2 , and SiCl_4 reactants at relatively low wall temperatures (less than 1000°K), the solid Si and alkali metal salt are rapidly codeposited onto the reactor surfaces in nearly stoichiometric proportions. No observable differences in deposition rate or product characteristics were produced by the presence of hydrogen in the diluent. Si from both sets of experiments was found to contain small amounts (1-3 ppm) of Fe and other metal impurities, and the Si was found to be a highly crystalline material.

For wall temperatures around 1225°K , little solid product of any kind was found on the reactor walls when the residence time was about 100 ms.

i. Production of Si from Bromosilanes -- J. C. Schumacher. Additional experimental data were obtained on the thermal decomposition of SiHBr_3 to produce Si, the results indicating that the reaction is proceeding to as high as 89% of completion. In other tests made to study the conversion of by-product SiBr_4 back to SiHBr_3 by reaction with H_2 in a bed of Si, conversion efficiency as high as 36% was obtained.

j. Purification of Si by the DS/RMS (Directionally Solidified/Refined Metallurgical Si) Process -- Union Carbide. This effort was negotiated and the contract put into final form.

k. Determination of the Effects of Impurities and Process Steps on Properties of Si and the Performance of Solar Cells -- Westinghouse/Dow Corning. Phase III of this study started in this period. The effort falls into five areas: (1) cell processing studies; (2) completion of the data base and impurity-performance modeling for n-base cells; (3) extension of p-base studies to include contaminants likely to be introduced during Si production, refining, or crystal growth; (4) anisotropy effects; and (5) a preliminary study of the permanence of impurity effects in Si solar cells.

The dominant activity during this quarter was the growth of ingots for the activities described above. Fourteen Czochralski (CZ) ingots were produced including several baseline ingots, p-base ingots for processing studies, and large-diameter ingots for the anisotropy investigation. Data on cellular breakdown in four of the heavily doped ingots was consistent with predictions; that is, structural breakdown due to constitutional supercooling is a characteristic of all ingots grown from heavily doped melts. At higher growth rates, the onset of breakdown occurs at lower impurity concentrations. There is a corresponding effect on the effective segregation coefficients in

that the closer the slices lie to the region where structural breakdown occurs, the nearer is the impurity concentration to that of the melt. Changes in concentration of 4 to 5 orders of magnitude within a few centimeters are common.

Besides the crystal growth, a detailed deep-level transient spectroscopic (DLTS) analysis of the electrical activity of Ti in Si was performed, and modeling studies of impurity behavior were extended. The DLTS experiments confirmed that two predominant Ti levels exist in Si regardless of whether Czochralski or float-zone growth is employed. The levels are insensitive to CZ pull rate. There was a direct correlation between the electrically active Ti and the total metallurgical Ti concentration in the ingots; about 20% of the Ti is active.

Modeling of the wafer rinse time indicated that there is a trade-off in cleaning between soluble contaminants removed from and particulate contaminants deposited on wafers prior to heat treatment. The post heat treatment lifetimes are consistent with the model.

The previously developed impurity effects model was extended to describe solar cell behavior in low-resistivity and polycrystalline material. Data for Ti compare favorably with the model expectations for the polysilicon cells. Changes in recombination center behavior are required to rationalize the low-resistivity behavior.

l. Effects of Impurities -- C. T. Sah Associates. The computer model for Si solar cell performance using a transmission line equivalent circuit was extended to include thickness variation, different diffusion profiles for the emitter and the back surface field layer, and profiles for the recombination impurities and recombination impurity-vacancy complexes. Interband Auger recombination as well as many species of recombination centers were also incorporated into the model.

m. X-Ray Analysis of Si Wafers -- Materials Research, Inc. Using X-ray analysis by the Lang transmission technique, Si wafers from Westinghouse were examined to confirm previous results and to study new wafers. The results for all samples indicate the presence of varying amounts of dislocations and precipitates. Sample W-039 (Ni-doped) showed a bicrystal structure (the two crystals were 15° apart). Topographs of the seed end also showed that there may be two or three crystals in the same wafer, confirming that the problem involved may be due to the growth process. The other Ni-doped wafers did not show this kind of structure. Samples W-044 and W-069 (Fe-doped) had a very high dislocation density that blocked out other structure defects. Sample W-041, which was doped with Ni, Cr, and Cu, had a high dislocation density also, which indicates that there is a close relationship between the structure defect densities and the low solar cell performance that this material gave.

It was clear from the topographs received to date that the Fe-doped samples and Ni/Cr/Cu-doped samples had the highest dislocation and precipitate densities. If it is assumed that all

grown ingots were intended to be dislocation free, then it can be said in general that these impurities induce dislocations and cause precipitation in Si.

n. JPL In-House Si Processing Technologies. A 2-in.-diameter stainless steel fluidized bed reactor was constructed and instrumented with pressure transducers, flow monitoring meters, safety devices, and a data acquisition system to study the Si deposition from a fluidized bed in order to complement Task I contractual activities. A series of experiments was then performed. A coherent and dense deposition product of Si from SiH_4 pyrolysis on Si seed particles was obtained. The product exhibited the desirable characteristics of a free-flowing material. A high percentage conversion was achieved.

A 3-in.-diameter stainless steel continuous-flow pyrolysis reactor with product separation and collection subsystems as well as instrumentation and control panels was constructed. Silane pyrolysis experiments were conducted successfully, yielding useful information on morphology forms of Si products from SiH_4 pyrolysis. The results indicated the effects of temperature and SiH_4 concentration on its pyrolysis. A low-density, fine Si powder and dense Si chemical vapor deposition product were obtained from the reactor.

Fluidization behavior studies were conducted to simulate the fluid mechanics of high-temperature operation of an Si fluidization reactor.

Modifications were made in the model of Si particle growth in a fluidized bed reactor so that experimental results obtained in the current fluidized bed reactor can be correlated directly. Also, the equations and computer code for a one-dimensional steady-state model of silane pyrolysis in the continuous flow pyrolyzer were derived.

o. Development of a Model and Computer Code to Describe Si Production Processes -- AeroChem Research. During this report period, mechanisms for the SiCl_4/Na and SiF_4/Na reaction systems were examined. Reaction schemes, including 25 elementary reactions, were formulated for each system and run to test the sensitivity of the computed concentration and temperature profiles to the values given to estimated rate coefficients. It was found that, for SiCl_4/Na , the rate of production of free Si is largely mixing-limited for reasonable rate coefficient estimates. For the SiF_4/Na system the results indicate that the endothermicities of many of the reactions involved cause this system to be chemistry-limited rather than mixing-limited.

Work continued on the problems of inserting particle nucleation and coagulation models into the code, and effort started on obtaining a suitable boundary layer code.

p. Studies of Process Feasibility and Economic Analysis -- Lamar University. Analysis of process system properties continued with major activities centered on properties of SiCl_4 , the source material for several alternate processes under consideration for solar-cell-grade Si. The following property data were reported for SiCl_4 : critical constants, vapor pressure, heat of vaporization,

gas heat capacity, liquid heat capacity, density, surface tension, gas viscosity, liquid viscosity, gas thermal conductivity, liquid thermal conductivity, heat of formation, and free energy of formation.

In the viscosity investigation, a constant-volume glass viscometer was fabricated and assembled for the measurement of gas viscosity values of Si source materials from 30°C to 350°C. In addition, calibration and evaluation of the gas viscometer previously assembled was initiated. Experimental work with gases of known viscosity, such as Ar and N₂, was conducted between 40°C and 200°C in order to evaluate the accuracy of data obtained on this viscometer. Using Ar as a reference, experimentally determined viscosity values for N₂ deviate from literature values by less than 2%.

The preliminary economic analysis of the Union Carbide Corporation SiH₄ process was completed. Cost, sensitivity, and profitability analysis results were obtained, based on a preliminary process design of a plant to produce 1000 MT/yr of Si by the revised process. Fixed capital investment estimate for the plant is \$9.19 million (1975 \$). Product cost without profit is \$6.90/kg of Si (1975 \$). The profitability results indicate a sales price of \$9.88/kg of Si (1975 \$) at a 20% DCF return on investment after taxes.

q. Purification of SiH₄ by Laser Apparatus -- Los Alamos Scientific Laboratory. Experiments showed that ternary mixtures of 1000 ppm each of phosphine (PH₃) and arsine (AsH₃) in SiH₄ can be purified to less than 4 ppm of both the PH₃ and AsH₃ without detectable loss of SiH₄. These results demonstrated the feasibility of the technique and provided verification of a simplified photochemical model for the process. A baseline case for the economic analysis of a laser purification add-on step to an SiH₄ production facility was established, indicating a cost for this purification of 5¢/kg of SiH₄ for a 1000 MT/yr plant.

B. LARGE-AREA SILICON SHEET TASK

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several alternative processes for producing large areas of Si sheet material suitable for low-cost, high efficiency solar photovoltaic energy conversion. To meet the objective of the LSA Project, sufficient research and development must be performed on a number of processes to determine the capability of each for producing large areas of crystallized Si. The final sheet growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

1. Technical Goals

Current solar cell technology is based on the use of Si wafers obtained by slicing large Czochralski or float-zone ingots (up to 12.5 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single crystalline Si wafers is tailored to the needs of large volume semiconductor products (i.e., integrated

circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of Si high-volume production techniques which would result in low-cost electrical energy.

Growth of Si crystalline material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e.g., hexagonal cross-sections) requiring very little manpower and machinery would also appear plausible. However, it appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

Research and development on ribbon, sheet, and ingot growth plus multiple-blade and multiple-wire cutting initiated in 1975-1976 is in progress.

2. Organization and Coordination

At the time the LSA Project was initiated (January 1975) a number of methods potentially suitable for growing Si crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured. The Large-Area Silicon Sheet Task effort is organized into four phases: research and development on sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype production development (1981-82); development, fabrication, and operation of production growth plants (1983-86).

3. Large-Area Silicon Sheet Task Contracts

Research and development contracts awarded for growing Si crystalline material for solar cell production are shown in Table 3-3. "Preferred" growth methods for further development during FY 1979-80 have been selected.

4. Large-Area Silicon Sheet Task Technical Background

a. Shaped Ribbon Technology: EFG Method -- Mobil-Tyco Solar Energy Corp. The edge-defined film-fed growth (EFG) technique is based on feeding molten Si through a slotted die as illustrated in Figure 3-1. In this technique, the shape of the ribbon is determined by the contact of molten Si with the outer edge of the die. The die is constructed from material that is wetted by molten Si (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/min and a width

Table 3-3. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
SHAPED RIBBON TECHNOLOGY	
Mobil-Tyco Solar Energy Waltham, Massachusetts (JPL Contract No. 954355)	Edge-defined film-fed growth (EFG)
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954376)	Ribbon growth, laser zone regrowth
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954654)	Dendritic web process
SUPPORTED FILM TECHNOLOGY	
Honeywell Corp. Bloomington, Minnesota (JPL Contract No. 954356)	Si on ceramic substrate
RCA Labs Princeton, New Jersey (JPL Contract No. 954817)	Epitaxial film growth on low-cost Si substrates
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem, Massachusetts (JPL Contract No. 954373)	Heat exchanger method (HEM), cast ingot, and multiwire fixed abrasive slicing
Kayex Corp. Rochester, New York (JPL Contract No. 954888)	Advanced CZ growth

Table 3-3. Large-Area Silicon Sheet Task Contractors (Continuation 1)

Contractor	Technology Area
INGOT TECHNOLOGY	
Siltec Corp. Menlo Park, California (JPL Contract No. 954886)	Advanced CZ growth
Texas Instruments Dallas, Texas (JPL Contract No. 954887)	Advanced CZ growth
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954374)	Multiblade slurry sawing
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954884)	Advanced CZ growth
DIE AND CONTAINER MATERIALS STUDIES	
Battelle Labs Columbus, Ohio (JPL Contract No. 954876)	Silicon nitride for dies
Coors Porcelain Golden, Colorado (JPL Contract No. 954878)	Mullite for container and substrates
Eagle Picher Miami, Oklahoma (JPL Contract No. 954877)	CVD silicon nitride and carbide
RCA Labs Princeton, New Jersey (JPL Contract No. 954901)	CVD silicon nitride
Tylan Torrance, California (JPL Contract No. 954896)	Vitreous carbon

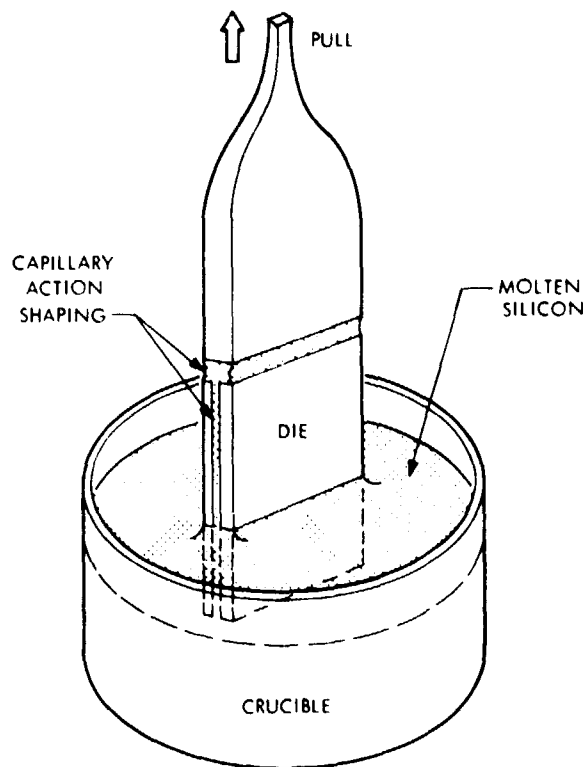


Figure 3-1. Edge-Defined Film-Fed Growth (EFG) -- Mobil-Tyco

of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

b. Shaped Ribbon Technology: Laser Zone Growth in a Ribbon-to-Ribbon Process -- Motorola. The ribbon-to-ribbon (RTR) process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline Si ribbon (Figure 3-2). The polysilicon ribbon is fed into a preheated region that is additionally heated by a focused laser beam, melted, and crystallized. The liquid Si is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

c. Shaped Ribbon Technology -- Westinghouse. Dendritic web is a thin, wide, ribbon form of single crystal Si. "Dendritic" refers to the two wire-like dendrites on either side of the ribbon, and "web" refers to the Si sheet that results from the freezing of the liquid film supported by the bounding dendrites. Dendritic web is particularly suited for fabrication into photovoltaic converters for a number of reasons, including the high efficiency of the cells that can be fabricated from it, the excellent packing factor of the cells into subsequent arrays, and the cost effective conversion of raw Si into substrates (Figure 3-3).

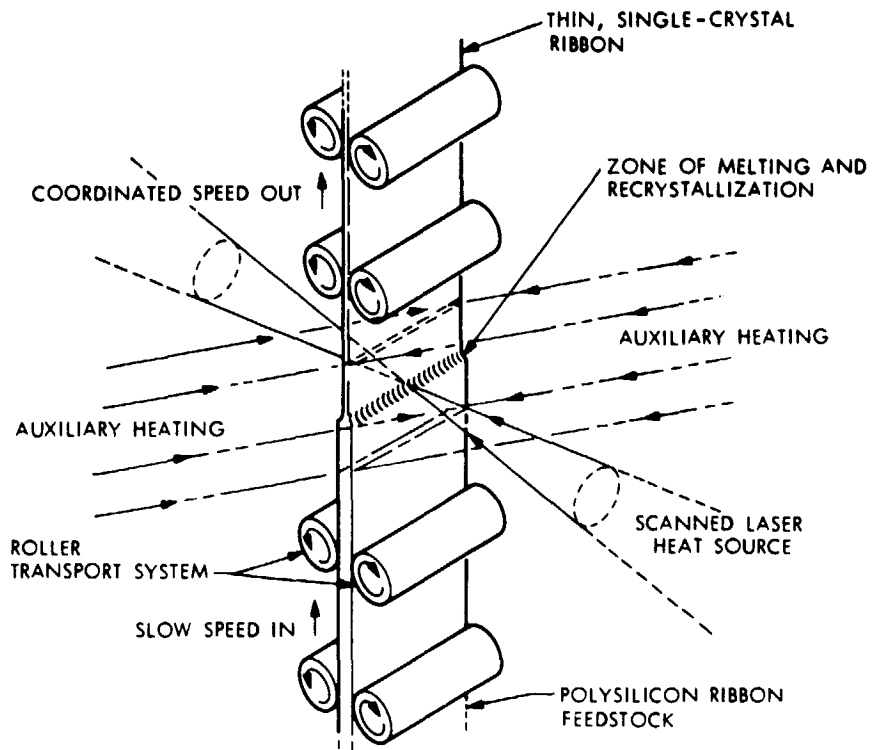


Figure 3-2. Laser Zone Regrowth -- Motorola

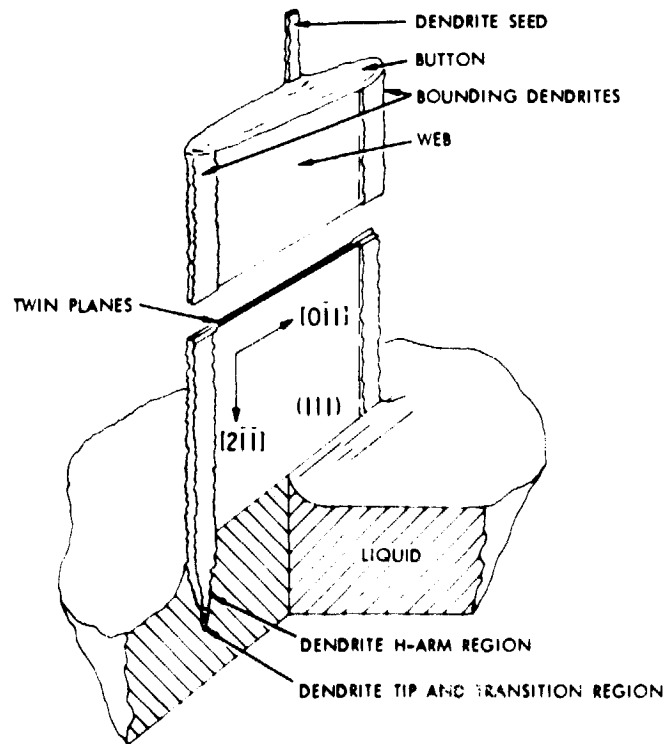


Figure 3-3. Schematic Section of Web Growth -- Westinghouse

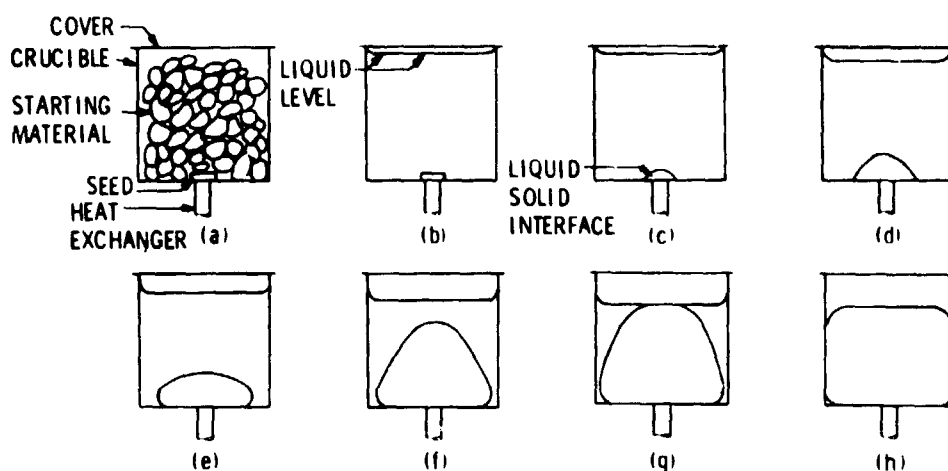
d. Supported Film Technology -- Honeywell. The purpose of this program is to investigate the technical and economic feasibility of producing solar-cell quality sheet Si by coating inexpensive ceramic substrates with a thin layer of polycrystalline silicon. The coating methods to be developed are directed toward a minimum-cost process for producing solar cells with a terrestrial conversion efficiency of 12% or greater. By applying a graphite coating to one face of a ceramic substrate, molten Si can be caused to wet only that graphite-coated face and produce uniform thin layers of large-grain polycrystalline Si; thus, only a minimal quantity of Si is consumed.

e. Ingot Technology: Heat Exchanger Method -- Crystal Systems. The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Figure 3-4). Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchanger ingot casting method can be applied to the growth of large shaped Si crystals (>8 in cube dimensions) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for Si.

f. Ingot Technology: Advanced CZ -- Varian, Texas Instruments, Siltec, and Kayex Corp. In the advanced CZ contracts, efforts are geared toward developing equipment and a process in order to achieve the cost goals and demonstrate the feasibility of continuous CZ solar-grade crystal production (Figure 3-5). Varian will modify an existing furnace for continuous growth using granular Si for recharging (molten Si will also be considered), and a new puller is to be designed. Texas Instruments' technique is based on an incoming flow of solid granular or nugget polysilicon, premelted in a small auxiliary crucible from which liquid Si will be introduced into the primary crucible. Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Kayex will demonstrate the growth of 100 kg of single crystal material using only one crucible by periodic melt replenishment.

g. Ingot Technology: Multiwire Sawing (MWS) -- Crystal Systems; Multiblade Sawing (MBS) -- Varian. Today most Si is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal. This is a large cost factor in producing solar cells. The multiblade and multiwire slicing operations employ similar reciprocating blade head motion with a fixed workpiece. Multiblade slicing is accomplished with a slurry suspension of cutting fluid



Growth of a crystal by the heat exchanger method:

- (a) Crucible, cover, starting material, and seed prior to melting.
- (b) Starting material melted.
- (c) Seed partially melted to insure good nucleation.
- (d) Growth of crystal commences.
- (e) Growth of crystal covers crucible bottom.
- (f) Liquid-solid interface expands in nearly ellipsoidal fashion.
- (g) Liquid-solid interface breaks liquid surface.
- (h) Crystal growth completed.

Figure 3-4. Crystal Growth Using the Heat Exchanger Method -- Crystal Systems

and silicon carbide abrasive and tensioned steel blades of 6 mm height and 0.2 mm thickness. Multiwire slicing uses 0.5 mm steel wires surrounded by a 0.25 mm copper sheet, which is impregnated with diamond as an abrasive.

h. Contact Material -- Battelle Labs, Coors Porcelain, Eagle Picher, RCA Labs, and Tylan. In the crystal-growing processes, a refractory crucible is required to hold the molten Si, while in the ribbon processes an additional refractory shaping die is needed. The objective of these contracts is to develop and evaluate cost effective refractory die and container materials. The material must be mechanically stable to temperatures above the melting point of Si, must not excessively contaminate the Si processed through it, be amenable to the fabrication of dies and containers with close tolerances and of varying geometries, and be cost effective. Two of the contracts in this area, RCA and Tylan, are to develop a substrate material for supported film growth and a coating for substrates, dies, and containers.

5. Summary of Progress

a. Shaped Ribbon Technology. Mobil Tyco -- A new EFG furnace is now operational. This machine provides unique observational tools, which should now begin to clarify several of the vexing problems in

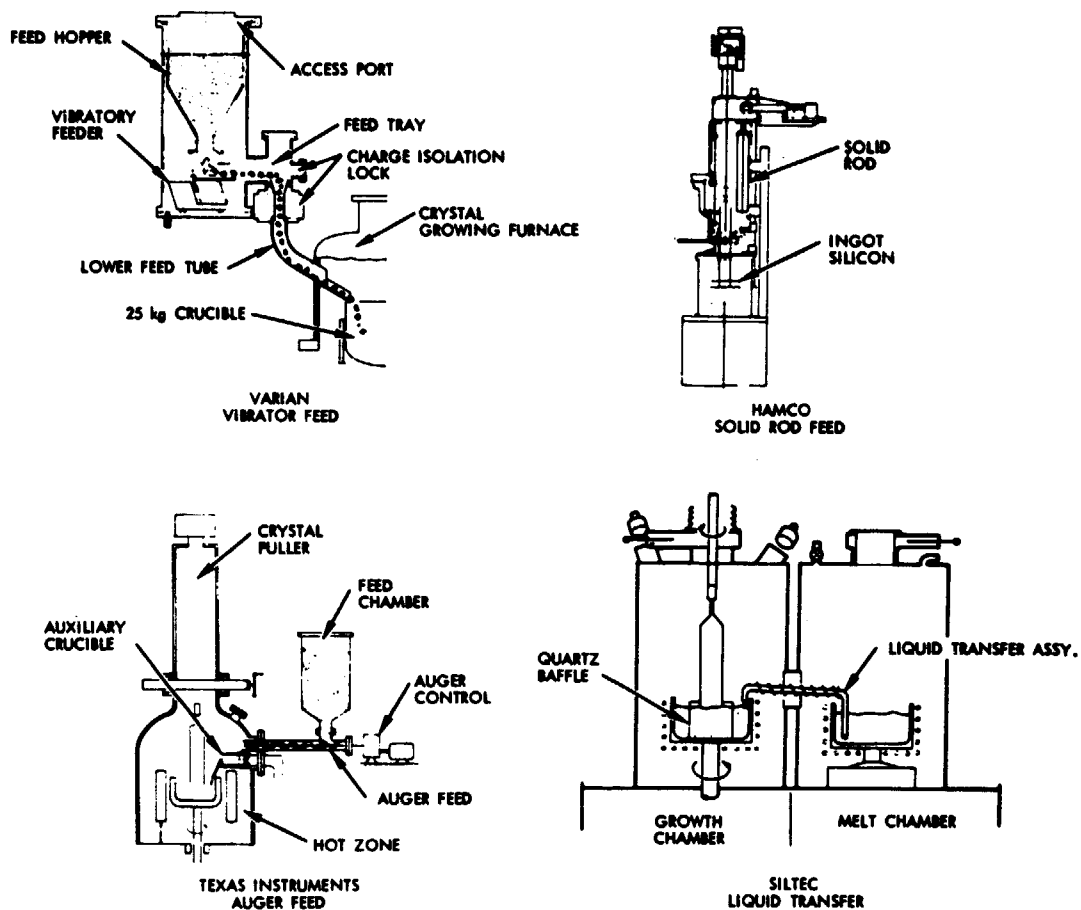


Figure 3-5. Continuous CZ Crystal Growth Machines

the growth from these resistance heated cartridge systems. Motorola -- A growth rate of $55 \text{ cm}^2/\text{min}$ with a single ribbon has been achieved. The solar cells have been fabricated on RTR Si grown from CVD feedstock. The highest efficiency ($\eta \sim 6\%$) was obtained on a sample grown from a polyribbon deposited on a Si_3N_4 coated Mo substrate. Westinghouse -- A manually operated continuous melt replenishment system was completed and installed in the research web growth facility. Initial results are encouraging. An afterheater with adjustable temperature and temperature gradient was installed in the J web growth facility. The initial results indicate minor modifications are necessary.

b. Supported Film Technology. Honeywell -- Two 5 cm substrates passed through the SCIM coater without breaking. Solar cell fabrication on dip coated slotted substrates was accomplished. The best slotted cell performance to date: 5.5% conversion efficiency (AM1, no antireflection coating), 2 cm^2 total area. RCA Labs -- A series of tests using a laboratory model rotary disc epitaxial reactor were completed. The overall yield, reproducibility, and cell efficiency have shown technical feasibility for this reactor concept.

c. Ingot Technology. Developments in the advanced Czochralski process are as follows: Kayex Corp. -- Experiments with a low-cost sand crucible were disappointing and judged not to justify further work at this time. Siltec Corp. -- The design of the transfer tube was completed. Texas Instruments -- A Czochralski crystal growing furnace was converted to a continuous growth facility by installation of a premelter to provide molten Si flow into the primary crucible. The best arrangement tested to date is a vertical, cylindrical graphite heater containing a small, fused Si test tube liner in which the incoming Si is melted and flows into the primary crucible. Varian (CZ) -- The crystal lift mechanism for the prototype puller was installed in the modified Varian 2850 furnace and was used to grow a crystal. Varian (MBS) -- The limits have been defined on blade thickness tolerances; 60% looser tolerances are unacceptable, while 30% looser tolerances seem acceptable. Mineral oil slurry with lubricity additive showed improvements over mineral oil alone.

d. Contact Material. Battelle Labs -- Mass spectrometric studies of molten Si in contact with mullite and β' Sialon ($\text{Si}_{6-x}\text{Al}_x\text{N}_{8-y}$ where $x = 0.75$) show that the vapor pressures of Si, silicon monoxide, aluminum, and alumina are very similar. In both cases the oxygen solubility is extremely low. Preliminary evaluation of the hot pressed silicon beryllium oxynitride materials with molten Si did not reveal any attack of these materials. Coors Porcelain -- Punched substrates of low-expansion mullite are now being routinely produced for use in the Honeywell program. Thermal expansion of this particular modification to mullite is identical with that of Si within the precision of measurement. Sessile drop and crucible testing efforts have indicated that uncoated mullite will not be a suitable material for containing molten Si for long periods. Eagle Picher -- Silicon nitride crucibles have been hot pressed and are now ready for application of the continuously nucleated thermal decomposition coating. RCA Labs -- Die plates of CVD Si_3N_4 and SiO_xN_y were fabricated for a capillary rise test. To date, die plates dipped into Si have not exhibited capillary rise.

C. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop and qualify a solar module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the module from the degrading effects of terrestrial environments. The most difficult technical problem is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments. In addition, significant technical problems are anticipated at interfaces between the parts of the encapsulation system, between the encapsulation system and the active module elements, and at points

where the encapsulation system is penetrated for external electrical connections. Selection of the element for the rear side (i.e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

Depending on the final solar array design implementation, the encapsulation system may also serve other functions (e.g., structural, electrical, etc.) in addition to providing the essential protection.

At present, options are being kept open as to what form the transparent element of the encapsulation system will take -- glass or polymer sheet, polymer film, sprayable polymer, castable polymer, etc. The transparent element may contain more than one material and may be integral with the photovoltaic device, or be bonded to it.

1. Organization and Coordination

The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations are being conducted to assure timely accomplishment of objectives.

During Phase I the contractor efforts and the JPL in-house efforts consisted primarily of a systematic assessment and documentation of the following items:

- (1) Potential candidate encapsulant materials based on past experience with the encapsulation of Si and other semiconductor devices, and on available information on the properties and stability of other potential encapsulant materials and processes.
- (2) The environment that the encapsulation system must withstand.
- (3) The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.
- (4) Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

The result of this effort will be used to specifically define additional research, development, and evaluation required during the subsequent phase.

Throughout the task atypical or unique approaches to solving the encapsulation system problem will be sought and evaluated. For example, Phase I includes an evaluation of the feasibility of utilizing electrostatically-bonded integral glass covers as part of the encapsulation system.

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulated systems and then verify the expected lifetime and reliability of these systems. Depending on the results of Phase I, the contractor effort in this phase will include an appropriate combination of some of the following items:

- (1) Evaluate, develop, and/or modify solar module testing and analytical methods and then validate these methods.
- (2) Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.
- (3) Modify materials and processes used in encapsulation systems to improve automation and cost potential.
- (4) Modify potential encapsulation system materials to optimize mechanical, thermal, and aging properties.
- (5) Implement research and development on new encapsulant materials.

2. Encapsulation Task Contracts

Encapsulation Task contracts are shown in Table 3-4. In addition, Professor Charles Rogers, Department of Macromolecular Science, Case Western Reserve University, serves as a consultant to this task (JPL Contract No. 954738) and will also implement selected supporting experimental investigations in the laboratories at Case.

3. Encapsulation Task Technical Approach

Program efforts to date have provided an assessment of the state of the art and a definition of the potential environmental and operational stresses imposed on the encapsulation system. A data base on candidate materials and their responses to these stresses is being accumulated and analyzed. Technology deficiencies are being experimentally exposed and documented.

4. Summary of Progress

The preparation of two RFP packages are in process: (1) development of encapsulation systems and (2) life prediction studies of encapsulation systems.

Two of the near-term cost reduction proposals selected for contract award have been assigned to the Encapsulation Task for technical monitoring. These are development of an AR coating for soda lime glass proposed by Motorola and development of glass-reinforced concrete (GRC) purposed by MB Associates for encapsulation system substrates. Statements of Work have been prepared for both contracts.

Table 3-4. Encapsulation Task Contractors

Contractor	Technology Area
Battelle Labs Columbus, Ohio (JPL Contract No. 954328)	Measurement techniques and instruments for life prediction testing
Case Western University Cleveland, Ohio (JPL Contract No. 954738)	System studies of basic aging and diffusion
Dow Corning Corp. Midland, Michigan (JPL Contract No. 954995)	Develop silicone encapsulation systems for terrestrial Si solar arrays
Endurex Corp. Dallas, Texas (JPL Contract No. 954728)	Ion-plating process and testing
Rockwell International Anaheim, California (JPL Contract No. 954458)	Test methods and aging mechanisms
Rockwell Science Center Thousand Oaks, California (JPL Contract No. 954739)	Materials interface problem study
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954521)	Electrostatic bonding process
Springborn Labs, Inc. Enfield, Connecticut (JPL Contract No. 954527)	Encapsulation test methods and materials properties evaluation

A contract in preparation in response to a Motorola unsolicited proposal to develop AR coatings for soda-lime glass is being changed to reflect the awarding of the near-term cost reduction contract to Motorola. A new unsolicited proposal has been received from Motorola which eliminates that part of the work covered by the near-term cost reduction proposal. A revised Statement of Work has been prepared.

The Rockwell Autonetics contract has been completed and closed out. The final report has been published and hardware delivered.

Negotiations are in progress for an extension of the SPIRE electrostatic bonding (ESB) contract for the next 16 months. Future work will consist of producing suitable ESB modules in semi-production quantities with research work concentrated on mesh interconnects, ribbon cells, and electrostatic bonding of high efficiency cells.

The encapsulation failure mechanism associated with the use of glass and polyvinylbutyral (PVB) has been investigated at JPL by examination of automobile windshields and wing windows on wrecked cars more than 20 years old. (The soda-lime glass/PVB/Mylar encapsulation system has been adopted by SAMIS as the base-line encapsulation system for costing purposes.) Edge yellowing and delaminations were observed with marked differences among specimens, but most damage even after 20 years was confined within 1/4 in. of the edge regardless of the presence or absence of an edge seal or gasket. Studies will be made to determine accelerated testing techniques to duplicate and quantify these degradation modes.

Encapsulation material systems have been selected and procurement initiated for the fabrication and test evaluation of candidate low-cost, glass-covered minimodules for 50¢/W strawman designs. Candidate material systems will include soda-lime and borosilicate glass, ethylene vinyl acetate, PVB, butyl rubber, Mylar, and aluminum foil. The minimodules are 12 x 16 in. in size and will be assembled with both round and rectangular solar cells including EFG ribbon cells. These minimodules are to be fabricated and testing initiated within the coming two months and will constitute a part of an expanded JPL in-house experimental program to utilize a standard minimodule approach to extensive evaluation of advanced module design and testing methods.

The experimental task of developing an ethylene/vinyl acetate (EVA) product optimized for automated processing, thermal stability, etc., is ongoing at Springborn. Also included are optimized adhesives, primers, acrylic UV screens, and other pottant candidates such as ethylenepropylene rubber (EPR) and polyvinylchloride (PVC).

Dr. Edwin Plueddemann of Dow Corning, a recognized authority in chemically reactive primers and adhesives, has agreed to participate in the LSA program as a consultant.

The Battelle Studies 3 and 6 have been completed and the final report, entitled "Evaluation of Available Encapsulation Materials for Low-Cost Long-Life Silicon Photovoltaic Arrays," has been distributed.

A generalized, preliminary test plan for the Battelle life prediction study of the Mead, Nebraska, array will be completed and presented to JPL for approval by October 31, 1978. A detailed test plan will be presented by Battelle at the December 1978 PIM and documented and sent to JPL by December 31, 1978.

Using the recently developed pin-hole free process for ion-plating, it has been conclusively demonstrated by Endurex that ion-plated coatings will not protect porous metallization systems. The dimensional scale of the coatings are inadequate to seal the

larger porous cavities and openings. Efforts with porous metallization will be abandoned and emphasis will shift to the ion-plated protection of solid metallization. To provide Endurex with an evaluation opportunity, its contract termination date has been extended from September 17, 1978, to December 31, 1978, at no cost to JPL.

With both its Phase I program plan and candidate materials approved, Dow Corning is proceeding to prepare encapsulated two-cell modules for its experimental program. In addition, Dow will initiate efforts at assessing thin films of silicone as possible UV screens.

A report, "A Preliminary View of Polymer Processing in Encapsulation," has been prepared in-house and will be distributed as an LSA report. Future work on automated processing will be concentrated on the selection of the most viable processing candidates and a review of the packaging industry and related equipment.

Modules received for failure analysis in-house included five with interconnect corrosion, four that virtually disintegrated after temperature cycling, one with severe delamination, and one with tempered glass superstrate failure. A module was received from Fort Belvoir with severe overheating and combustion of encapsulant materials. This phenomena has been duplicated on a test module by applying a reverse electrical bias. Tests were begun to determine the temperature caused by the reverse electrical bias by analysis of the thermal properties of the encapsulant materials.

SECTION IV

PRODUCTION PROCESS AND EQUIPMENT AREA

The objective of the Production Process and Equipment Area is to identify, develop, and demonstrate energy-conservative, economical processes for the fabrication of solar cells and arrays at a production price of less than \$500/kWpk. The schedule is shown in Figure 4-1.

The Production Process and Equipment Area effort is now in Phase II, Process Development. A milestone chart with the major milestones identified is contained in Figure 4-2. Phase II, initiated in September 1977, is well under way at this time. Processes are being developed in the four major areas of fabrication; that is, surface preparation, junction formation, metallization, and assembly. The contractors involved in these efforts are shown in Table 4-1.

In addition to the progress made by the various contractors during this quarter, the Production Process and Equipment Area group presented a \$500/kWpk strawman factory and a metallization workshop.

Figure 4-3 shows the 50¢/W candidate manufacturing sequence for the strawman factory. The techniques to be used and the contractors pursuing those techniques are shown in Figure 4-4. The added value cost goal and present technology, in addition to the technical milestones, are shown in Figure 4-5.

The objective of the metallization workshop, held the day before the beginning of the 10th Project Integration Meeting, was to explore problems and potential improvements. The approach concentrated on bringing together people from a wider range of disciplines relating to metallization, selecting presentations from established and novel metallization techniques, and discussing merits and shortcomings of processes presented.

The workshop divided the history of the metallization effort into three areas:

- Plating semiconductors -- electroplate various metals; electroless nickel-sinter; electroless gold/nickel; and electroless palladium-sinter-nickel.
- Vacuum evaporation -- noble metals; aluminum; titanium/silver; titanium/palladium/silver; and chrome/titanium/molybdenum, gold/palladium, and silver/copper.
- Printed thick films -- decorating dishes (gold/platinum); passive electrical networks (silver/gold/platinum and nickel/silver-palladium); and solar cells (silver).

Metallization requirements were determined to be: cost effectiveness, adhesion to Si, good ohmic contact, chemical

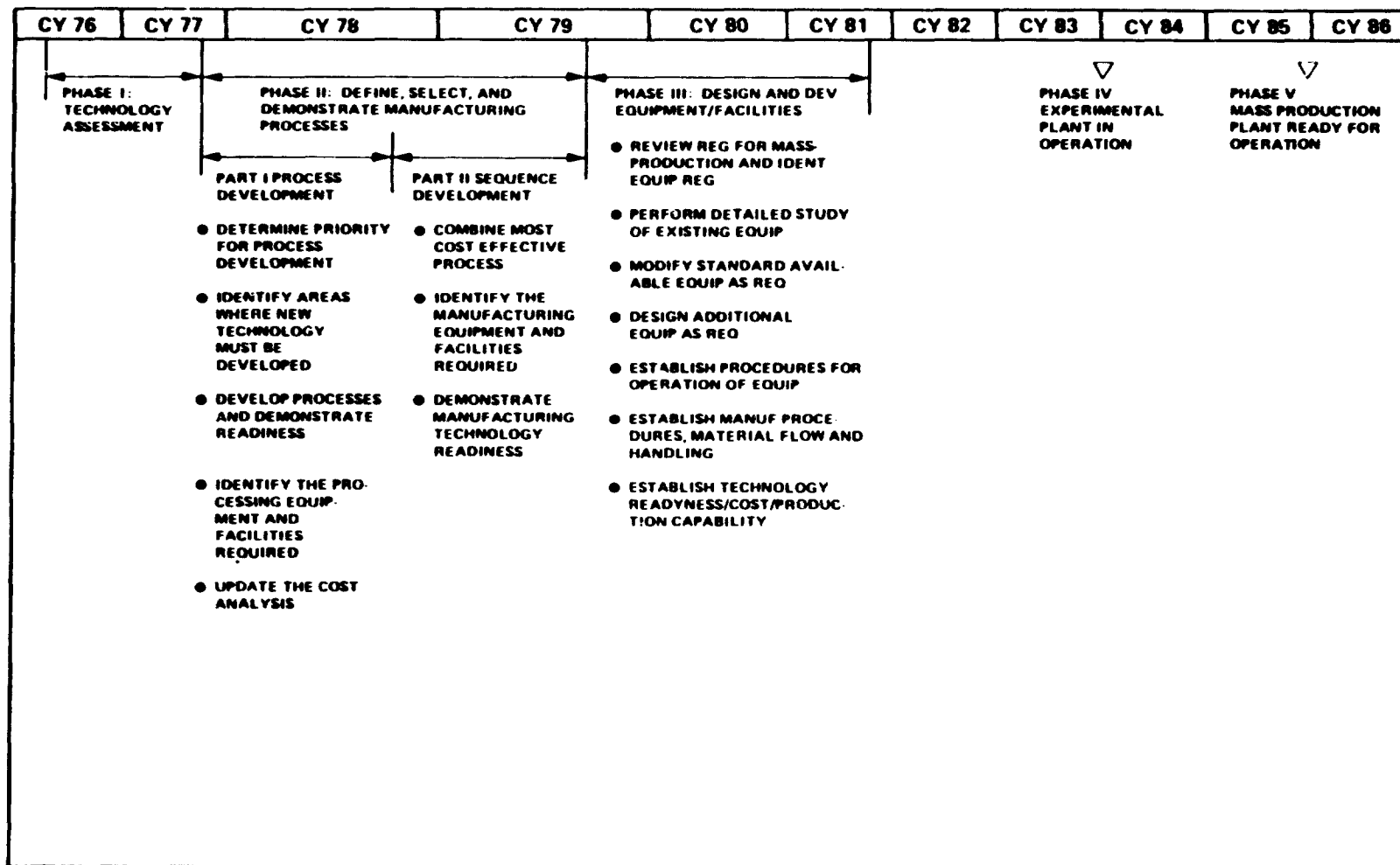


Figure 4-1. Production Process and Equipment Area Schedule

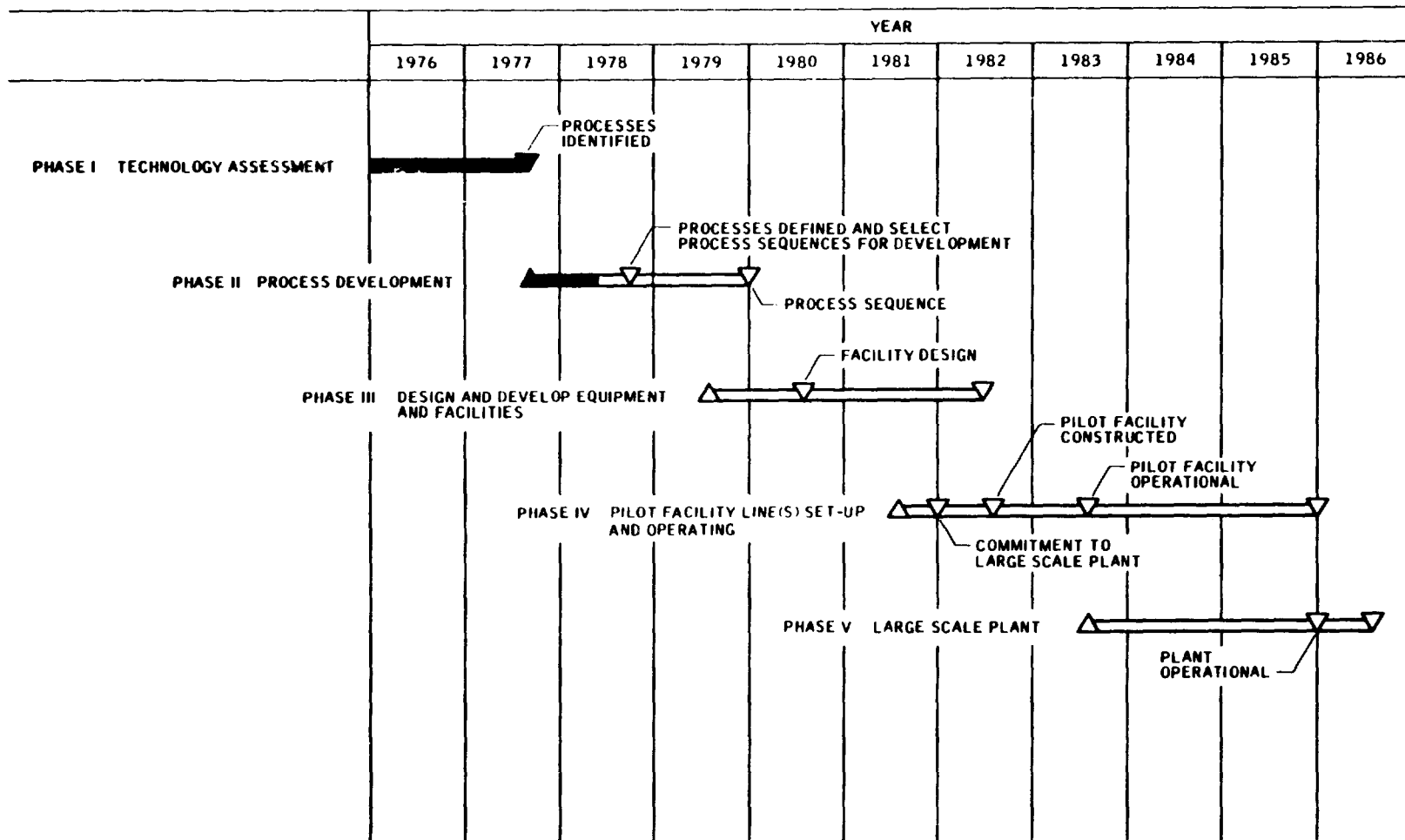


Figure 4-2. Production Process and Equipment Area Major Milestones

Table 4-1. Production Process and Equipment Area Contractors

Contractor	Type Contract	Technology Area
General Electric R&D Philadelphia, Pennsylvania (JPL Contract No. 954607)		Shingle-type modules
Kinetic Coatings, Inc. Burlington, Massachusetts (JPL Contract No. 955079)		Ion implantation
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954410)		Spraylon
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954898)	Phase II	Process development
Mobil Tyco Solar Waltham, Massachusetts (JPL Contract No. 954999)		Developmental solar modules
MBA San Ramon, California (JPL Contract No. 954882)	Phase II	Process development
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954363)		Technology assessment
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954689)		Metallization of Si wafers
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954716)		Parallel oriented interconnects
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954847)	Phase II	Process development
Optical Coating Lab City of Industry, California (JPL Contract No. 954831)		High efficiency, long-life solar panels
Optical Coating Lab City of Industry, California (JPL Contract No. 954830)		Slicing

Table 4-1. Production Process and Equipment Area Contractors
(Continuation 1)

Contractor	Type Contract	Technology Area
Optical Coating Lab City of Industry, California (JPL Contract No. 955118)		Ion implanter invest.
RCA Corp. Princeton, New Jersey (JPL Contract No. 954868)	Phase II	Process development
Sensor Technology Chatsworth, California (JPL Contract No. 954605)		High efficiency panels
Sensor Technology Chatsworth, California (JPL Contract No. 954865)	Phase II	Production process sequence
Solarex Corp. Rockville, Maryland (JPL Contract No. 954822)		High density panels
Solarex Corp. Rockville, Maryland (JPL Contract No. 954854)	Phase II	Process development
Solarex Corp. Rockville, Maryland (JPL Contract No. 955077)		Wafer thickness evaluation
Spectrolab, Inc. Sylmar, California (JPL Contract No. 954853)	Phase II	Process development
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954786)		Ion implanter
University of Pennsylvania Philadelphia, Pennsylvania (JPL Contract No. 954796)		Automated array
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954873)	Phase II	Process development

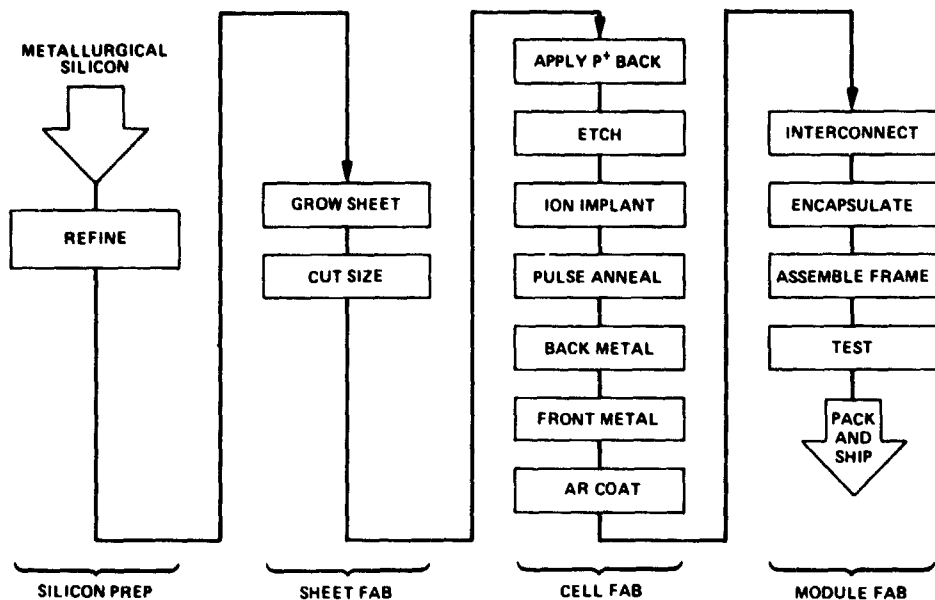


Figure 4-3. 50¢/W Candidate Manufacturing Sequence

KEY PROCESS	OPTIONS	CONTRACTORS
SHAPING	LASER SCRIBING, SAWING	SENSOR TECH, WESTINGHOUSE S.O.A.
BACK SURFACE FIELD	ALUMINUM GROUP III POLYMERS ION IMPLANTATION CVD DIFFUSION	SOLAREX, ARCO, SPECTROLAB SENSOR TECH SPIRE, MOTOROLA WESTINGHOUSE, RCA S.O.A.
SURFACE PREPARATION	PLASMA WET CHEMICAL	MOTOROLA, TEXAS INSTRUMENTS S.O.A.
JUNCTION FORMATION	ION IMPLANTATION DIFFUSION GROUP V POLYMERS	KINETIC COATINGS, MOTOROLA, LMSC, RCA, SPIRE S.O.A. SENSOR TECH, SOLAREX, SPECTROLAB, TEXAS INSTRUMENTS
ANNEAL	PULSE FURNACE	SPIRE, LMSC S.O.A.
METALLIZATION	PLATING THICK FILM	MOTOROLA, SENSOR TECH, SOLAREX LMSC, ARCO, RCA, SPECTROLAB
AR COATING	CVD SPRAY SPUTTER EVAPORATE	MOTOROLA LMSC, RCA KINETIC COATINGS S.O.A.
INTERCONNECT	SOLDER WELDING	S.O.A. RCA, SOLAREX

Figure 4-4. Techniques for Manufacturing Sequence

PROCESS INVESTIGATION	ADDED VALUE COST GOAL	PRESENT TECHNOLOGY	KEY TECHNICAL MILESTONE NEEDED TO BE DEMONSTRATED
BACK SURFACE FIELD	0.002	0.018/0.040	AUTOMATION DEMO REQUIRED
SURFACE PREPARATION	0.010	0.015/0.100	INCREASED THROUGHPUT
JUNCTION FORMATION	0.011	0.038/0.480	LARGER ION IMPLANTER
ANNEAL	0.018	0.027/0.041	DEVELOP PULSE/SCAN PROCESS
METALLIZATION	0.070	0.020/0.564	CONSISTANT RELIABILITY
AR COATING	0.008	0.017/0.274	PROCESS DEMONSTRATED, EQUIPMENT AVAILABLE
INTERCONNECT	0.042	0.600/2.000	AUTOMATION DEMO REQUIRED
ASSEMBLE	0.120	0.400/10.000	GLASS SUPERSTRATE DEMONSTRATED AUTOMATION DEMO REQUIRED
TEST AND PACK	< 0.002	0.032/0.500	LARGE MODULES - INCREASED THROUGHPUT

Figure 4-5. Cost Goals, Present Technology, and Milestones for Factory

stability, junction preservation, and good conductivity. Other design considerations include back surface field, interconnections, and process compatibility.

Discussions on low-cost electroless plating came to the following conclusions:

- Advantages -- metal deposited only where used; follows surface contours; nickel is corrosion resistant; palladium forms very stable silicide.
- Limitations -- requires patterning process; sensitive to surface contamination; and requires build-up for electrical conductivity (solder dip, electroplate, etc.).
- Areas for improvement -- systems that do not penetrate the junction when used over reasonable manufacturing tolerances, and reducing the number of processing steps.

Discussions on low-cost thick film printing came to these conclusions:

- Advantages -- metal deposited only where used; can be thick enough for good conductivity; easily automated; and tolerant of surface contamination.
- Limitations -- requires firing in oxidizing atmosphere; presently restricted to silver; contains glass (non-conductive) frit; and mechanically stresses Si sheet.
- Areas for improvement -- develop metal frit and low-cost metals.

Novel methods receiving attention during the workshop were: hybrid systems (trapped conductors over grids and plated or evaporated grids with thick-film bus conductors), ion plating, chemical vapor deposited metal, pulse sintering, transfer tapes, ultrasonic soldering, a printed-photo system (Du Pont Fodel), and plated metal powders.

The general work performed by contractors during this quarter is summarized below.

A. TECHNOLOGY ASSESSMENT

The University of Pennsylvania completed a comparison of the current crystal-growing costs with projected future costs, and cautions that all of the future costs are based on assumed advances in technology that have not yet been fully demonstrated.

B. SURFACE PREPARATION

Sensor Technology reported that it has been able to reduce the costs of cell manufacturing to 21.37¢/Wpk, largely through cost-effective wafer surface preparation studies. It reported a reduction in this area from 6.39¢/Wpk to 1.55¢/Wpk. These values are based on IPEG calculations.

Kinetic Coatings, Inc., has reported the effective application of aluminum trioxide to texturized wafers. RCA, working on synthesizing AR coatings, has been concentrating on titanium isopropoxide and titanium ethoxide as secondary solvents to the already-developed materials tested. Since both are effective, the guiding principle is simply volume cost information.

C. JUNCTION FORMATION

SPIRE has produced the design specifications for a 100 milliamp ion implanter to produce wafers at 1¢/Wpk by a SAMICS analysis. It has also produced back surface fields by boron ion implant with an efficiency of 14.1% at air mass zero. Lockheed reports the effective use of laser annealing producing cells with air mass 1 efficiencies on an average of 12.3%. Electron beam annealing equipment was outlined for design by SPIRE. These two different approaches are being taken simultaneously to evaluate their effectiveness against furnace annealing. The spray-on machine developed by Advanced Concepts has been delivered to Sensor Technology and initial tests have been performed. Although the machine is operational, preliminary tests are being conducted to establish the key parameters related to spray-on performance and through-put rates.

D. METALLIZATION AND CONTACTS

Motorola reports that work on a palladium-nickel metallization formulation was completed. The formulation, developed entirely by Motorola, consists of fabrication of layers of palladium silicide, followed by electroless palladium, then electroless nickel, and finally covered with a lead-tin solder by dipping. IPEG calculations indicate a cost of 4.17¢/Wpk for a 12-cm diameter wafer.

E. ASSEMBLY AND TEST

Laser holing and hexagonal scribing equipment was delivered to Sensor Technology this quarter and has been demonstrated to be effective. A laser scribing and holing automation study was also completed by Quantronics through Sensor Technology and included a description and cost breakdown of the laser equipment needed to produce cells of this nature. Westinghouse has reported the manufacturing of dendritic web cells that have efficiencies as high as 15.9%.

F. ADVANCED MODULE DEVELOPMENT

The final three of six contracted modules manufactured from Mobil-Tyco Si ribbon material were delivered. Design improvements eliminated some of the previous problems. Two of the three modules were subjected to JPL Test Specification 5-342 and passed all of the environmental requirements.

SECTION V

ENGINEERING AREA

During the quarter, the Engineering Area has continued activities in the areas of array design guidelines, reliability-durability requirements, and array specifications and standards.

In the area of design guidelines, the draft final reports were received from Bechtel Corporation and Boeing Engineering. The Bechtel contract generated data defining optimum module/array structural configurations for central power applications. A key output of the study was the cost sensitivity to structure configuration and wind loading level. The use of a curved glass module design suggested by the study appears to be cost-effective. Review of the Boeing air-supported module enclosure study results indicates that the concept has potential cost advantages. An important conclusion emphasized the need for improved definition of wind loading levels on conventional arrays. In-house activities included modification and improvement of the series/parallel computer program in order to interface with a new module replacement strategy program. The married programs evaluate the extent to which series/parallel arrangements influence or reduce life-cycle costs. The series parallel program was also used to perform "hot-spot" analysis on 4P x 12S modules intended for the National Park Service application. A contract was initiated with Burt, Hill, Kosar, Rittleman and Associates (Butler, Pennsylvania) to develop residential module design guidelines and requirements. Following an in-house assessment of module electrical termination design technology status, an RFP was issued for a termination design requirements study applicable to 1986 modules.

In the area of reliability-durability testing, work was initiated on an in-house effort in conjunction with JPL Fracture Mechanics materials specialists to characterize the mechanical breaking strength of Si solar cells. Initial results characterized resistance of terrestrial cells to various bending and flexing modes. These results provided initial inputs to conceptual designs of improved fracture strength testing methods and fixture designs. An improved fixture will be fabricated and tested next quarter. Work on module soiling included design of a particulate deposition chamber for measuring deposition affinities of various encapsulants and initiation of a dust accumulation data collection agreement with the South Coast Air Quality Management District. A combined high voltage stress and dust accumulation field test was designed and construction of the installation initiated. The Clemson University cell reliability testing contract was expanded to include mechanical peel strength of contact metallization. The minimodule testing program at DSET Laboratories continued through the quarter, and the exposure contract add-on covering FY79 activities was negotiated. Preliminary thermal and spectral distribution mapping of the Super-EMMAQUA was accomplished. Work was initiated on design of a standard minimodule for support of encapsulation and process development studies.

In the area of specifications and standards, a summary report, LSA internal document 5101-76, was issued covering recent thermal testing activities which provided, as an appendix, the new test method for measuring nominal operating cell temperature (NOCT). Preliminary drafts of design and test specifications for future intermediate load center and residential modules were generated and submitted to peer review. The specifications are intended for use in future large-scale procurements. Support to SERI photovoltaics standards efforts continued through the quarter. Environmental testing methodology information was supplied to the reliability/durability subcommittee, and support was provided in developing an outline for the Interim Performance Criteria. Engineering Area personnel participated in both advisory committee and subcommittee capacities.

SECTION VI
OPERATIONS AREA

A. SUMMARY OF PROGRESS

1. Large-Scale Production Task

a. Block III. A total of 36.2 kW of modules were delivered this quarter. This represents 46% of the amount projected for delivery at the beginning of the quarter. While this is an improvement over the performance vs plan achievement in the last quarter, there is still a significant gap between production projecting and actuals. Several unanticipated problems arose during the quarter at more than one contractor that resulted in the abbreviated delivery quantities. These problems are addressed in the Technical Data section of this report.

b. Block IV. During this quarter, the RFP for Block IV was reviewed by the JPL Evaluation Committee and submitted to the formal JPL approval cycle.

2. Environmental Testing

The first of the three new temperature-humidity chambers was set up in a temporary location in Building 144. It became operational early in the quarter, with the result that no modules had to be sent off Lab for testing during this quarter. The other two chambers should be operational at Building 188 in the next quarter.

Testing of Block III qualification and production samples continued during this quarter. No electrical failures resulted, although miscellaneous minor physical degradation was noted. Three types of developmental modules and six types of commercial modules were also tested, with widely varying results depending on the manufacturer and the module type. Details are given in the Technical Data section.

3. Field Testing

During the early part of this quarter, the Point Vicente Site was brought on line, thus completing the network of remote sites. On August 9, deployment of a subarray of each of the Block II modules was made. The configuration of those modules is the same as the other remote sites; no Block I modules will be deployed at Point Vicente. Arrangements have been made to obtain routine weather data from the resident Coast Guard personnel.

A draft of the Field Test Annual Report was submitted for editing in mid-September. Publication of the report is expected early next quarter.

A tightening up of routine testing procedures at the JPL Site occurred this quarter: A one-week washing schedule was initiated in

an attempt to reduce the I_{sc} deviation when compared with previously obtained data -- this strategy resulted in a measurable decrease in the deviation. A closer monitoring of all modules was initiated; suspicious modules are being more closely tracked. A more formal schedule of equipment maintenance has been initiated and a formal schedule for the archiving of data has been established.

During this quarter and the latter part of the last quarter, five dirt accumulation tests were performed, two using the field data system and essentially the whole field of modules, and three with the large area pulsed solar simulator (LAPSS) facility and the six subarrays dedicated for this purpose. The Technical Data section summarizes the results.

4. Performance Measurements and Standards

During the course of evaluating early production Motorola modules, it was determined that these modules had spectral responses different from the cells delivered earlier, from which the Motorola reference cells were fabricated. The difference was significant in that errors of 4% to 8% were produced in LAPSS testing. For this reason, a new group of reference cells was fabricated and delivered to Motorola, with companion cells being retained at JPL.

Deviations of greater than 3% between measurements at JPL and two vendors have occurred, necessitating an investigation into the causes of the discrepancies. One problem was found to be caused by a peak-to-peak intensity variation, from the center to the edge of the test plane of the manufacturer's solar simulator, of approximately 7% with the reference cell located near the high intensity. Relocation of the reference cell to the median intensity was performed as the non-uniformity is invariant. The second problem was caused by a steady decline in the blue response of delivered modules from another manufacturer. Since this manufacturer's tungsten simulator is red-rich, the loss of blue response was not observed there, but could be seen in the JPL LAPSS. This problem was especially evident in the recently delivered modules, in which differences of more than 10% were commonly observed.

Preparations are under way to provide reference cells to the Phase I contractors for the flat-plate PRDA experiments. Due to the shortness of the schedule, these cells will be mounted on balloon flight hardware and calibrated with the JPL tracking facility. Since the standard atmosphere does not occur at JPL, these references will only be $\pm 2\%$.

The second LAPSS computer system was received, set up, and is now in the process of being checked out. Hardware and software interfacing of the computer with the two LAPSSs has been initiated. It is not clear at this time where the LAPSS facilities will be located, but it is planned that one LAPSS will always be operational during the move and integration phases.

5. Failure Analysis

Activity for this quarter included the generation of 21 new problem/failure reports (P/FRs) and the closure of 19 analyses. At the end of this quarter, the reporting system had a total of 347 P/FRs, of which 246 had been closed. Summaries and pertinent analytical results have been distributed to the four test and application projects. Applicable P/FRs have been sent to all affected manufacturers.

The problem/failure reporting rate is increasing from both JPL field test and applications experiments. The total number of module problems related to field exposure is now 72. The most common problems/failures are interconnects, cracked cells, and delamination of encapsulant. Open circuits or other electrical degradation is generally caused by cracked cells or broken interconnects, although in several modules the cause of open circuits has been found to be unsoldered cell or terminal connections. The delamination problems relate to material selection, cleaning, surface preparation, and processing.

B. TECHNICAL DATA

1. Large-Scale Production Task

a. Block III. The production detail for the quarter is shown in the following table:

<u>Contractor</u>	<u>kW Allocated</u>	<u>kW Shipped July-Sept.</u>	<u>kW Shipped Total</u>	<u>% Complete</u>
ARCO Solar, Inc.	37.15	4.89	9.11	24.5
Motorola, Inc.	50.00	8.79	8.89	17.8
Sensor Technology, Inc.	40.00	5.22	8.60	21.5
Solar Power Corp.	53.07	10.80	23.40	44.1
Solarex Corp.	<u>31.91</u>	<u>6.50</u>	<u>30.30</u>	<u>95.0</u>
Total	212.13	36.20	80.30	37.8

During this quarter, the contracts with ARCO Solar, Inc., Solar Power Corp., and Solarex Corp. have been modified to accommodate the change in apparent power resulting from the systematic calibration error in reference cells described in previous reports. Measurements are in various stages of completion, which will allow needed modifications to the contracts with Motorola and Sensor Tech.

Several problems affecting the rate at which modules are delivered to JPL have arisen during the quarter. At ARCO, it was found that the lead protective tape at the ends of the module was

ungrounded, which posed a potential safety hazard. Delivery was stopped while an acrylic edge protector was designed and installed in order to preclude field problems.

At Motorola, start-up problems continued to affect the production line, but by the end of the quarter the yield was approaching a satisfactory level. Sensor Tech deliveries were slowed by a shortage of 2-in. Si wafers from which Sensor Tech fabricates its solar cells. This difficulty suggests that solar module designs should call for 3-in. or 4-in. cells because ingot manufacturers prefer to grow these sizes. Solar Power slowed delivery during this period in order to clean up its processes and improve the yield.

Although deliveries have not been made on the schedules planned at the outset, no test and application project is suffering from an inadequate supply of modules.

2. Field Testing

Table 6-1 presents the results of soiling tests at the Pasadena site. The values presented in the table are the percent decrease in I_{sc} due to dirt, normalized to a 30-day period. Tests 1 and 3 were with the whole field, and Tests 2, 4, and 5 were with the "dirt" modules. Except for the first test, all the data show a dirt effect of 6% to 8% for a 30-day period, regardless of surface material. In addition to the data presented, two Block II Solar Power and one Block II Spectrolab were left in the field dirty from June 5 through September 5. The I_{sc} differences between the dirty and clean LAPSS flashes at the end of the period was 18% to 20% for all three modules. The two Solar Power modules showed residual dirt effects of 3% and 7%. The glass-faced Spectrolab module, as expected, showed no residual effect.

3. Environmental Testing

a. Production Task Block III Modules. Several environmental qualification tests of initial allotment and of production sample modules were run this quarter and are summarized in Table 6-2. One case of an interconnect soldering problem was detected on one module of the V type. The Z type showed frequent delamination at interconnects, but only very small areas. Also, a cell crack was found in each of two modules of the three initial Z modules tested.

One R module was discovered with one terminal open. Failure analysis showed that none of the cell busbars had been soldered to the four terminal screws. A second R module had only 25 Ω resistance to ground. Although no actual environmental testing has been started on R modules this quarter, there has been considerable activity. Delay in getting reference cells prevented an early start on these modules. The manufacturer uses two different types of cells, with the result that a double set of tests will be required. Thermal coefficients and performance measurements were made on each of the two types. These tests indicate that the voltage at maximum power was nearer 5.0 V than the 4.5 V previously estimated.

Table 6-1. Dirt Test Summary

Module Type	Surface	Quantity	Test Results (% Change in I_{sc})				
			Test 1 5/25-6/15	Test 2 6/5-7/10	Test 3 6/30-7/31	Test 4 7/11-8/7	Test 5 8/9-9/5
Sensor Tech I	Silicone rubber	57	3.5		6.6		
Spectrolab I	Glass	38	4.1		6.5		
Solarex I	Silicone rubber	34	4.8		7.0		
Solar Power I	Silicone rubber	7	5.6		6.8		
Sensor Tech II	Silicone rubber	34	3.0		6.1		
Sensor Tech II	Silicone rubber	8		6.3		5.9	5.7
Spectrolab II	Glass	13	3.6		7.1		
Spectrolab II	Glass	3		7.5		7.5	6.5
Solarex II	Silicone rubber	17	3.2		6.8		
Solarex II	Silicone rubber	4		6.6		6.5	5.8
Solar Power II	Silicone rubber	13	4.2		7.1		
Solar Power II	Silicone rubber	3		5.8		5.8	5.0
ARCO	Glass (stippled)	5		6.6		7.0	7.6

Table 6-2. Test Results on Block III Modules

Mfr.	Tests Completed This Quarter	Type of Modules In Array	Results
R	None		Prior to environmental test, it was found that none of the four terminal connections were soldered on one module. Another module had low resistance to ground.
V	Qual	Initial	Whitish contamination on all external electrical terminals.
V	T ~ only	First set, production samples	One module with open circuit; no solder on back contacts of one cell.
Y	Qual	Second set, production samples	Satisfactory
Y-HD	T ~ only	Initial	Satisfactory
Z	Qual	Initial	Delamination at interconnects and at frame seal; one cell crack on each of two modules.
Z	T ~ only	First set, production samples	Interconnect delamination.

Tests on currently available Block III modules were run in which one cell in a module was half shadowed during a LAPSS flash. All module types showed considerable performance sensitivity to shadowing, as would be expected from the Block II experience. The R module with four parallel cell strings showed the least sensitivity.

b. Automated Array Assembly Task Modules. Module Types K, L, and M were tested this quarter. Type K is designed for use as a residential shingle (see 9th LSA Quarterly Report). The first test of four modules resulted in one with a shattered glass cover after temperature cycling. Since there was some indication that the fracture was caused by impact, the test was run again with four new modules. This time the modules were nailed to a piece of plywood covered with building paper to simulate a roof installation. A special vacuum fixture and a "fishscale" was used individually on each module for the mechanical integrity test.

Type L is made of EFG ribbon cells, 20 x 100 mm each. The cells are encapsulated in Silgard 184 between two sheets of glass. There were some problems with intermittent continuity because of loose terminal screws. These screws are mechanically secured to the rear glass plate. Attempts to carefully tighten the nuts cracked one glass. The module consists of four submodules mounted on aluminum side rails. Each submodule contains three rows of 15 shingled cells. The entire module is 32 x 122 cm (12.62 x 48 in.). The extra length required special subarray frames as well as new pressure plates for the mechanical integrity (wind simulation) fixture. These modules can be accommodated in the same size test equipment that will be required for Block IV modules; these L modules provided an opportunity to design and try out the new, larger test equipment.

Type M is the high density, large (59 x 177 cm) module with shingled cells, as described in the 9th LSA Quarterly Report.

The results of the tests are given in Table 6-3.

c. Commercial. Six types of commercial modules were tested. Brief descriptions are given in Table 6-4 and test results are in Table 6-5.

Table 6-3. Test Results on Task 4 Modules

Mfr.	Tests Completed This Quarter	Results
K	Qual	All four modules tested were damaged at the joint between the glass laminate (hexagon) and the rectangular soft Hypalon during the mechanical integrity test. One module had 4 cm tears on each side of the hex. Another had one 15 cm tear.
L	T~ and H~ only	One module OK; the other had a number of delaminated areas near the cells.
M	Qual	Severe cover glass cracking and delamination on one module in T~. Lesser cover cracks on second module, severe delamination.

Table 6-4. Descriptions of Commercial Modules Tested

Vendor	Size (cm)	Cells	Description
CA	Encap. cells only w/tabs for inter-connection		Individual 7.5 cm dia. encapsulated cells, 10 cm dia. overall. For this test, 16 cells were connected in series.
CB	25 x 25	16 of 53 mm dia.	Cells held between two layers of heavy molded glass nested together and sealed.
CI	24 x 55	50 mm sq., 40, welded intercons.	Cells encapsulated between two layers of glass with an aluminum channel frame.
CJ	35 x 45	36 of 57 mm dia.	Epoxy fiberglass substrate, silicone encapsulant.
CM	30.5 x 76	36 of 76 mm dia.	Aluminum frame and substrate, glass cover. Encapsulant may be RTV 602, RTV 11, or PVB.

Table 6-5. Results of Commercial Module Tests
(Commercial Tests Are Temperature Cycling and Humidity Only)

Vendor	Results
CA	Of the 16 cells in the "module," one cracked, nine showed delamination. Electrical degradation of individual cells varied from zero to 45%.
CB	Satisfactory
CI	Satisfactory
CJ	Marginal electrical degradation on two of four modules.
CM (RTV 602)	Cover glasses cracked on all four modules. Some delamination on one.

Table 6-5. Results of Commercial Module Tests (Continuation 1)
(Commercial Tests Are Temperature Cycling and Humidity Only)

Vendor	Results
CM (PVB)	Test terminated at 21 temperature cycles when a power outage and chamber restart caused the temperature to drop to about -57°C (-17°C overshoot). All glass covers cracked. Gasket between glass and frame appears to have shrunk. Test will be rerun if more modules can be obtained.

4. Failure Analysis

Table 6-6 summarizes module problem/failure experience for this quarter.

Table 6-6. Summary of P/FR Activity

Mfr.	Procurement Block	New P/FRs	Closed P/FRs	Environmental Test	Field Test	Application Centers
V	Block I	1			1	
	Block II		1	1		
W	Minimodules	2		2		
	Block I		3		2	1
Y	Block I	1	1		1	1
Z	Block I	5	5		5	5
	Block II		9	9		
	Block III	4				
	Task 4 Developmental	5		5		
	Task 5 Commercial	3		3		

Table 6-7 summarizes the total problem/failure experience in field test and applications.

Table 6-7. Summary of Field Test Application Experience

Mfr.	Procurement Block	JPL Field Test	LeRC	MIT/LL	DOD
V	Block I Block II	5	4	6	
W	Block I	3		3	
Y	Block I Block II	4	4	7	2
Z	Block I Block II	18	3	4	9
Total		30	11	20	11

a. Manufacturer V. Block I failure relates to broken interconnect at the terminal junction and extensive delamination of the encapsulant around the edges of the module.

b. Manufacturer W. Three Block I modules had failures analyzed. One module had an unsoldered terminal post, which caused over-heating at that point; two modules had electrical degradation, which was attributed to cracked cells.

c. Manufacturer Y. Two Block II modules were reported to exhibit electrical degradation after mechanical integrity test. Cause of the less than 6% power drop has not been determined.

d. Manufacturer Z. One Block I module analyzed was found to have a fractured interconnect. Five other modules are suspected to have the same problem. Eight Block II modules were reported to have cracked cells. It was concluded that entrapped air underneath the cells had caused these fractures during temperature cycling tests.

Four Block III modules have been reported to have cracked cells and delamination of encapsulant as a result of environmental test.